# XBT AND CTD TEMPATURE MEASUREMENT COMPARISON AND XBT AND GDEM SOUND VELOCITY PROFILE COMPARISON

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# INTRODUCTION

A variety of instrumentation and technology is available for sampling and processing oceanic field station data. The sophistication and ability to regularly calibrate many of today's conductivity temperature and depth (CTD) profilers make them the instrument of choice for oceanographic field sampling, particularly in research applications. However, the nature of current naval operations and fiscal constraints, render the CTD profiler impractical as an expedient tool to obtain temperature versus depth profiles. The expendable bathythermograph (XBT) remains the primary method for relatively low cost, quick acquisition of temperature versus depth information in the operational field for sound velocity profile (SVP) determination by naval forces. Yet, the reduced sophistication of the XBT when compared with the CTD presents an inherent risk of lower quality data and potential biases that must be identified. If naval forces have access to a satellite internet connection, the Generalized Digital Environmental Model (GDEM) is another source that they can draw upon to obtain oceanographic data. However, before using this data to make tactical decisions its accuracy must be determined.

The Naval Postgraduate School's winter 2006 Operational Oceanography class conducted a two-leg research cruise aboard the R/V Point Sur in California coastal waters between Moss Landing and Long Beach from 19 to 26 January 2006. The first leg departed Moss Landing, CA on 19 January and completed on 22 January in Port San Luis with a student turnover, and leg two concluded on 26 January with a Tactical Oceanography student turnover in Long Beach, CA.

This study has two aims. The first is to compare the temperature versus depth profiles obtained in this cruise using the XBT against temperature versus depth profiles obtained using the CTD at the same sampling stations. The second is to compare the sound velocity profiles obtained in this cruise using the XBT against sound velocity profiles generated using GDEM data obtained from the Naval Oceanographic Office website. This paper will include a review of data collection methods, results, and a discussion with mention of previous studies and the impact of sound velocity profile errors upon naval operations.

## DATA COLLECTION

The CTD-XBT comparison was comprised of thirteen collocated XBT/CTDs of which six were obtained during cruise one and seven during cruise two. The locations of each collocated XBT drop and CTD cast are listed in Appendix A and plotted in Appendix B. In order to enhance clarity and render the data analysis easier, the XBT launches and CTD casts used in the comparison were renumbered 1 through 13 and therefore the numbers do not coincide with the numbers recorded in the laboratory log/cruise report. Most of the data collection locations had a water depth of over 1000 meters, so the entire data set from XBTs could be analyzed. The only exception was site 12, which was shallower; data was only collected to a depth of 745 meters. The Sippican T-7 XBT has an operational depth of 760 meters. The CTD can be lowered to a desired depth and was generally lowered to a depth of 1010 dbar (1000 m); however, depth restrictions at site 12 limited that CTD to a depth of 752 dbar (745 m).

After the cruise ended, the GDEM data was extracted from the NAVO website. The database access mode was ‘single point’, that is, a single latitude and longitude were

entered along with the calendar month, and the website returned depth, salinity, temperature and sound velocity data from the GDEM site that was the closest to the operator entered location. For the purposes of this study, the locations entered into the website were the latitude and longitude of the XBT firings. The location of each GDEM data extraction point and the distance from the XBT firing location are recorded in Appendix A. The GDEM locations are plotted in Appendix B.

The XBT records depth in meters while the CTD references depth in decibars. The XBT records temperature in degrees Celsius, as does the CTD. GDEM returns depth in meters and sound velocity in meters per second. All data was saved in ASCII file format for ease of ingestion by Mathworks MATLAB 7.1.

## METHODS OF QUALITY CONTROL

MATLAB 7.1 was used for data extraction, computations and plotting. 39 ASCII data files (13 XBT, 13 CTD and 13 GDEM) were edited and loaded into MATLAB. Pressure measurements from the CTD were converted into depth measurements using a seawater routine m-file. A script m-file was written to extract the depth and temperature data from each XBT and CTD file, and depth and sound speed data from each XBT and GDEM file. Each profile was scanned visually and by the computer for bad data points. Bad data was rejected, and statistics were performed on the good data.

The first quality control check was to plot the temperature profile of each XBT and CTD data set, and sound speed profile of each XBT and GDEM data set. The goal was to visually identify any bad information. In this manner, the XBT-8 profile was seen to be corrupt below 630 meters. The temperature versus depth XBT-8 profile is included in Appendix C. There was no indication of how this data file was damaged. The copper

wire of the XBT may have possibly made contact with the ship and caused the spike. Whatever the reason, all of the XBT-8 data below 630 meters was replaced with NaN (not a number) for lack of accurate digitized readings.

Following visual inspection, a MATLAB program was used to compile the data into separate matrixes: a XBT temperature matrix, a CTD temperature matrix, a XBT sound speed matrix, and a GDEM sound speed matrix. MATLAB then compared the data point at each level in one matrix to the average of the data in the levels above and below it in the same matrix. In particular, each data point was compared to the average of the temperatures or sound speeds of the surrounding two levels. If the data point differed by more than two standard deviations from the average of either of the surrounding levels, it was identified as a possible bad data point, and flagged for further investigation. For the top and bottom levels, only one level was available for comparison.

The total number of data points checked was 11022 (4906 XBT temperature + 4973 CTD temperature + 571 XBT sound speed + 572 GDEM sound speed). Of these, 207 CTD (4.16%) and 202 XBT (4.12%) were identified as possibly bad data points. No GDEM data points were identified as possibly bad. All were looked at more closely, and found to be part of a logical sequence decreasing with depth in the case of the temperature data points, or approaching a constant as the depth increased in the case of the sound speed data points. Therefore, all of the data points run through the MATLAB routine were considered reasonable and consistent, and no further data was excluded.

## METHODS OF DATA PROCESSING

Due to the high accuracy and calibration of the Sea-Bird CTD, the CTD temperature measurements were considered to be the true representation of the

temperature profile. All temperature comparisons were made comparing the XBT temperature data to the CTD temperature data, and any differences are assumed to reflect inaccuracies in the XBT measurement. Since a CTD is not available on most naval vessels to obtain the most accurate oceanographic information for generation of sound speed profiles, an XBT is the most accurate method available to obtain sound speed data for generating the sound speed profile. All sound speed profile comparisons were made comparing the XBT sound speed data to the GDEM sound speed data, and any differences are assumed to reflect inaccuracies in the GDEM data.

After converting the CTD data sets to temperature versus depth vice pressure, each CTD data set had a temperature sample for approximately every 2 meters of depth. The XBT data was already measured with reference to meters, but the data was recorded in 0.6 meter increments. A MATLAB program was used to linearly interpolate the XBT temperature data sets to the CTD measurement depths. Another MATLAB program was used to linearly interpolate the XBT sound speed data sets to the GDEM measurement depths. After the interpolation was complete, I performed the quality check described in the previous section.

For each XBT/CTD pair, the XBT temperature at each depth was subtracted from the CTD temperature. Two plots were made for each pair. The first contained the temperature profile for each sensor. The second showed the temperature difference at each level. These plots are shown in Appendix D. For the 13 sets, temperature differences were combined, and the mean and standard deviation determined by MATLAB for all levels. These statistics are plotted in Figure 1.

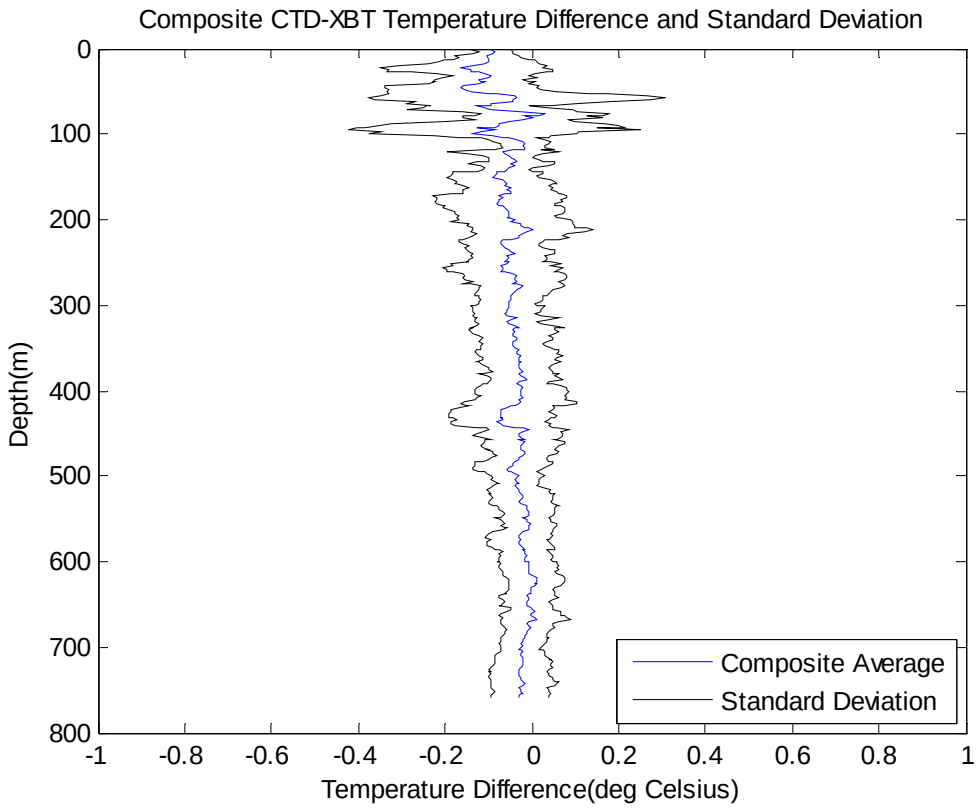



***Figure 1.*** *The mean and standard deviation of temperature differences from the 26 collocated CTD and XBT drops.*

For each XBT/GDEM pair, the XBT sound speed at each depth was subtracted from the GDEM sound speed. Two plots were made for each pair. The first contained the sound speed profile for each sensor (The CTD sound speed profiles were also included in these graphs). The second showed the sound speed difference at each level. These plots are shown in Appendix E. For the 13 sets, sound speed differences were combined, and the mean and standard deviation determined by MATLAB for all levels. These statistics are plotted in Figure 2.

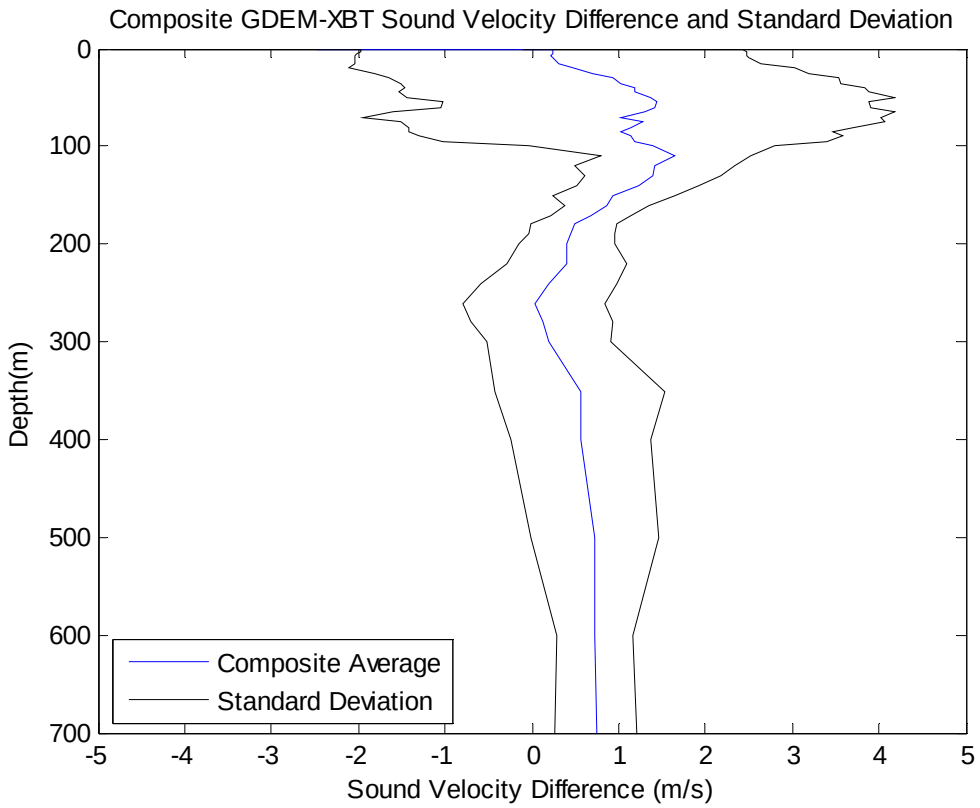



***Figure 2.*** *The mean and standard deviation of sound speed differences from the 26 XBT drops and GDEM data extraction locations.*

## RESULTS

The mean and standard deviation of the temperature difference between the XBTs and CTDs were determined for 383 levels between the surface and 760 meters. The XBT temperatures ranged between 0.0287°C colder to 0.1621°C warmer than corresponding CTD measurements and had an average warm bias of 0.0407°C overall. The maximum average temperature difference was observed at 21 meters and below 200 meters the average temperature difference was less than 0.028°C and generally decreased with depth, meaning the XBT readings were closer to the CTD readings at depth.

The greatest variability of the temperature differences was observed in the upper 200 meters. The greatest standard deviations occurred in the upper levels; the maximum

standard deviation of 0.342°C was observed at 57 meters. The standard deviation below 200 meters was 0.08°C and also generally decreased with depth.

It should be noted that many of the large magnitude temperature differences occurred in the upper levels. The large vertical temperature gradients in the upper levels demonstrate that many of the apparent temperature differences are in fact depth differences. Therefore, if the depth difference exists, the stronger temperature gradients result in larger temperature differences.

A similar study was published in 1983 by Heinmiller et al. Heinmiller et al. studies both Sippican T-4 and T-7 XBTs and used a calibrated Neil Brown CTD. The portion of the Heinmiller et al. study comparing the T-7 XBT to the CTD was conducted in the Sargasso Sea and consisted of 139 casts.

Also, five previous OC3570 similar studies of CTD and XBT profiles have been performed by Schmeiser (2000), Roth (2001), Boedeker (2001), Fang (2002), and Dixon (2003). Schmeiser's, Roth's, Boedeker's, Fang's and Dixon's study compared 18, 9, 27, 28, and 24 CTD/XBT pairs respectively. This study performed statistics on 13 pairs. All compared Sippican T-7 XBTs to a Sea-Bird CTD onboard the R/V Point Sur along the central Californian coast.

Schmeiser (2000) provides a detailed comparison of the data collection and editing techniques of the Heinmiller et al. (1983) with his study. Since the techniques of this study are very similar to those of Schmeiser (2000), a detailed comparison of Heinmiller et al. (1983) with this study would be redundant and readers are referred to Schmeiser (2000).

In this study, as in Roth (2001), Boedeker (2001), Fang (2002) and Dixon (2003), the XBT data was interpolated before being quality checked. This was not determined to have a significant effect in comparing against Schmeiser's data which was quality checked before interpolation. Since the XBT sampling interval is so small, quality control after interpolation will have little effect on the outcome of the quality control (Roth, 2001). Table 1 is a summary of the significant findings of the five studies. As can be seen in Table 1, the results of this study are very similar to the results from the previous five studies. All show a warm bias in the XBT measurements that is most pronounced in the upper portion of the water column and generally decreases with depth. The greatest standard deviations also occur in the upper levels.

| Studies | Depth (m) | Mean (°C) | Std (°C) |
|---|---|---|---|
| Schmeiser Aug-00 | 25-125 | -0.2198 | 0.3598 |
| | 175-375 | -0.1212 | 0.1981 |
| | 0-760 | -0.1549 | 0.2151 |
| Roth Feb-01 | 25-125 | -0.0907 | 0.1779 |
| | 175-375 | -0.0851 | 0.0960 |
| | 0-760 | -0.0783 | 0.1047 |
| Boedeker Aug-01 | 25-125 | -0.1530 | 0.5135 |
| | 175-375 | -0.0549 | 0.2157 |
| | 0-760 | -0.0882 | 0.2147 |
| Fang Jul-02 | 25-125 | -0.2453 | 0.4123 |
| | 175-375 | -0.0802 | 0.1172 |
| | 0-760 | -0.1074 | 0.1546 |
| Dixon Feb-03 | 25-125 | -0.2366 | 0.1009 |
| | 175-375 | -0.1010 | 0.0193 |
| | 0-760 | -0.1275 | 0.0598 |
| Laird Jan-06 | 25-125 | -0.0760 | 0.1622 |
| | 175-375 | -0.0453 | 0.0992 |
| | 0-760 | -0.0407 | 0.0936 |
| Average | 0-760 | -0.0995 | 0.1404 |

***Table 1.*** *Mean and standard deviation of CTD-XBT temperature differences on NPS OC3570 cruises aboard R/V Point Sur.*

In the second half of the study, the mean and standard deviation of the sound speed difference between the XBTs and the GDEM sites were determined for 44 levels between the surface and 700 meters. The XBT sound speeds ranged from 2.4796 meters per second faster to 1.6535 meters per second slower than corresponding GDEM data and had an average slow bias of 0.7272 meters per second overall. The maximum average speed difference was observed at the surface and generally decreased with depth, meaning the XBT measurements were closer to the GDEM data at greater depths.

The greatest variability of the sound speed differences was observed in the upper 150 meters. The greatest standard deviations occurred in the upper levels; the maximum standard deviation of 2.9826 meters per second was observed at 70 meters. The standard deviation below 150 meters was 0.65 meters per seconds and also generally decreased with depth.

The five OC3570 studies that were previously completed focus solely on an analysis of the implications of a bias in temperature differences and depth differences. None of them examined sound velocity profiles obtained from GDEM to determine the differences between data collected via an XBT as opposed to extracting it from an online database. The next section considers the tactical implications of using an XBT instead of a CTD and using data obtained from GDEM instead of an XBT.

## DISCUSSION

The results of the previous five student projects are generally consistent and this study is in agreement with the results of these studies (Table 1). The selected depth categories of 25-125 meters and 175-375 meters were selected first by Schmeiser (2000) and could be considered somewhat arbitrary. Other depth categories may form a better

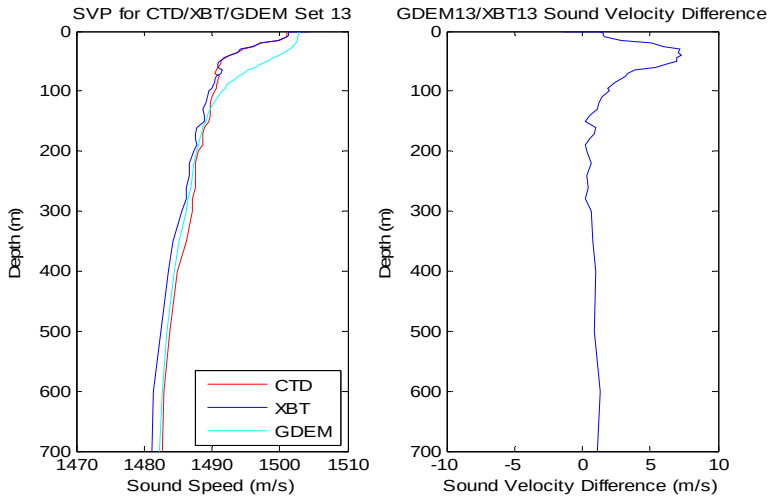
basis for research such as those correlating to accepted definitions of the mixed layer and thermocline, however, these depth categories have been retained to facilitate a consistent method of comparison among studies. The XBT exhibits a systematic error of higher temperature readings. The warm bias in the XBT measurements is most pronounced in the upper portion of the water column and generally decreases with depth. The increased warm bias and variability in this layer is consistent with the greatest change of temperature with depth in the thermocline layer and is to be expected.

XBTs are the primary instrument for developing SVPs for the Navy for use in USW operations. The results of this study indicate that a warm bias is introduced by the XBT but the question of exactly how this warm bias affects the SVP must be addressed. The average warming bias introduced by the XBT in this study is 0.0407°C (Table 1) and from all student cruises is 0.0995°C. A 1°C increase in temperature will roughly increase the sound speed by 4 meters per second. (Urick, 1983). As shown in Schmeiser (2000), a bias of 0.4°C would change the computed sound speed by only 1.6 meters per second, about 0.1% of the average 1500 meters per second sound speed. The average bias of 0.0407°C presented by this T-7 XBT in this study would increase the average speed of sound by only 0.163 meters per second. Since the XBT bias is almost constant throughout the entire profile, the sound speed will be affected roughly the same amount at each depth. Sound speeds are only nominally increased by the warm bias of the XBTs and the sound speed gradients are not appreciably affected. Therefore it is concluded that the sound speed and sound speed gradient change is not appreciably affected by the warm bias of the XBT and sound velocity measurements obtained by the XBTs are not

impacted significantly enough to impose an operational degradation upon the USW problem.

While not posing a problem in an operational use, the consistent warm bias could negatively impact climate studies. As with all data, biases should be removed before using it to draw conclusions. Scientists relying on these XBT profiles to look for global warming without accounting for the bias would see a rise in ocean temperature even if there was no change, and an even higher rise if there was. A well designed experiment could determine an inherent bias and a correction that could be applied to XBT data collected around the world. The sample size in this study, in addition to the temporal and spatial variation, is not sufficient for such a determination.

When examining the sound velocity difference between the XBT and GDEM data it is tempting to conclude that the XBT slow bias of 0.7272 meters per second is not significant enough of a difference to affect the tactical use of SVP utilizing GDEM data. However, even small differences in the profiles can have a large impact tactically. Take for example, the data from site #13:



As noted in Appendix A, site #13 was the location were the XBT firing and the GDEM extraction point were the closest together compared to the other sites (~ 2.2 nautical miles).

Examining the graph on the left, the XBT SVP indicates that the mixed layer depth is 20 meters deep and has a sharp gradient. Due to the sharp gradient, a target submarine will use that relatively flat spot on the curve and calculate his "best depth" for silent operation based on that depth, which appears to be about 20 to 25 meters shallower than the GDEM SVP. If the operator on the surface ship trying to locate the submarine was using the GDEM SVP, this could make a difference for direct path detection with a towed array since he would place the towed array at the wrong depth. There is not a huge vertical difference, but it would give a surface vessel a false sense of security about the performance of its sonar dome on submarines in the previously mentioned depths. The difference in the gradients that define the layer depth between the GDEM and XBT data might change the effectiveness of the shadow zone effect for submarines just below the layer; once again, the GDEM data would underestimate this effect.

Another reason the GDEM data looks so different from the XBT data might be due to the time-averaging nature of GDEM. In SOCAL, thermal radiation tends to change the SVP dramatically, and an XBT SVP could look like the associated GDEM trace at mid day. If I was running a comparison in a tropical climate or away from a large cold current, there might not be as much of a difference between the GDEM and XBT traces.

This study reveals that although an XBT SVP is a good approximation to a CTD SVP, GDEM SVPs often will miss important features in the water column, and should not be used for tactical operations. Whenever possible, naval vessels should rely on

recently fired XBTs to obtain accurate SVPs. Future research should attempt to use a larger sample size of collocated profiles from different locations. As Roth (2001) suggests, the XBT should be released before the CTD to reduce temporal variation. Different batches of XBTs should also be used if possible, since using XBTs with different manufacturing dates will further generalize the results.

## REFERENCES

Boedeker, S., "Comparison of CTD and XBT Temperature Profiles." Paper submitted for OC3570, 2001.

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Roth, M.J., "XBT and CTD Temperature Measurement Comparison, Quality of JJYY Data and XBT Data Analysis of the Mixed Layer Depth." Paper submitted for OC3570, 2001.

Schmeiser, G., "XBT and CTD Temperature Measurement Comparison." Paper submitted for OC3570, 2000.

Urick, R.J., 1983: *Principles of Underwater Sound*. 3rd ed. McGraw-Hill, pp. 423.

**APPENDIX A**

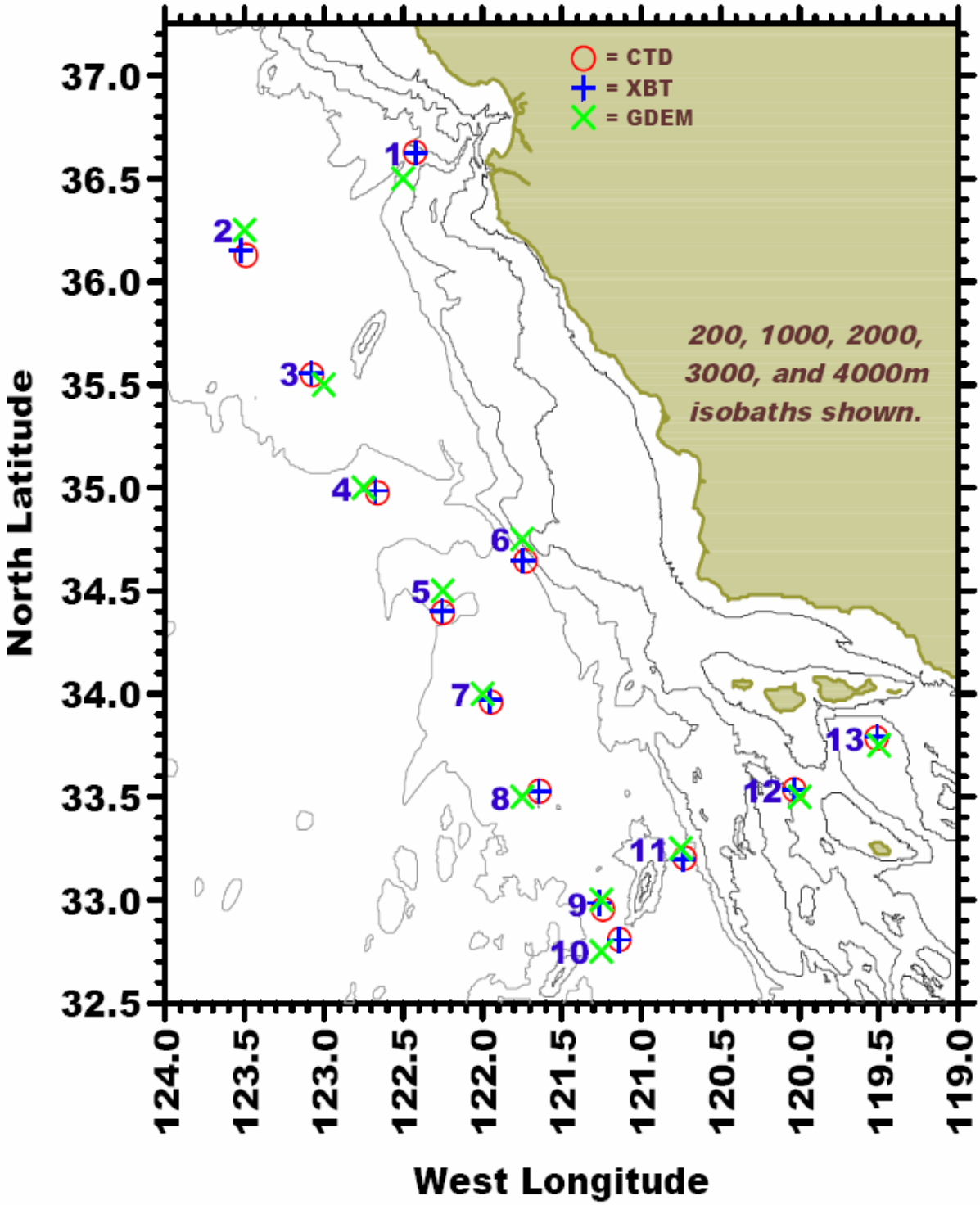
Location of CTD and XBT Temperature Profiles

| Pair No. | XBT No. | XBT Latitude North | XBT Longitude West | CTD No. | CTD Latitude North | CTD Longitude West | Date |
|---|---|---|---|---|---|---|---|
| 1 | 2 | 36.625 | 122.42 | 4 | 36.627 | 122.424 | 20 Jan 06 |
| 2 | 3 | 36.151 | 123.522 | 10 | 36.127 | 123.491 | 20 Jan 06 |
| 3 | 4 | 35.556 | 123.079 | 15 | 35.548 | 123.073 | 21 Jan 06 |
| 4 | 5 | 34.987 | 122.674 | 19 | 34.975 | 122.662 | 21 Jan 06 |
| 5 | 6 | 34.401 | 122.256 | 23 | 34.395 | 122.249 | 21 Jan 06 |
| 6 | 7 | 34.647 | 121.746 | 26 | 34.644 | 121.728 | 22 Jan 06 |
| 7 | 8 | 33.969 | 121.954 | 36 | 33.959 | 121.946 | 23 Jan 06 |
| 8 | 9 | 33.526 | 121.645 | 39 | 33.528 | 121.641 | 23 Jan 06 |
| 9 | 10 | 32.984 | 121.263 | 43 | 32.955 | 121.24 | 24 Jan 06 |
| 10 | 11 | 32.806 | 121.137 | 44 | 32.808 | 121.136 | 24 Jan 06 |
| 11 | 12 | 33.196 | 120.736 | 47 | 33.203 | 120.726 | 24 Jan 06 |
| 12 | 13 | 33.534 | 120.036 | 53 | 33.535 | 120.035 | 25 Jan 06 |
| 13 | 14 | 33.792 | 119.513 | 59 | 33.785 | 119.516 | 25 Jan 06 |

| GDEM Site No. | GDEM Latitude North | GDEM Longitude West | Distance between XBT Location and GDEM Location (nm) |
|---|---|---|---|
| 1 | 36.5 | 122.5 | 8.433 |
| 2 | 36.25 | 123.5 | 7.393 |
| 3 | 35.5 | 123 | 4.583 |
| 4 | 35 | 122.75 | 4.579 |
| 5 | 34.5 | 122.25 | 6.3 |
| 6 | 34.75 | 121.75 | 6.452 |
| 7 | 34 | 122 | 3.643 |
| 8 | 33.5 | 121.75 | 5.706 |
| 9 | 33 | 121.25 | 2.747 |
| 10 | 32.75 | 121.25 | 6.722 |
| 11 | 33.25 | 120.75 | 3.067 |
| 12 | 33.5 | 120 | 2.734 |
| 13 | 33.75 | 119.5 | 2.247 |

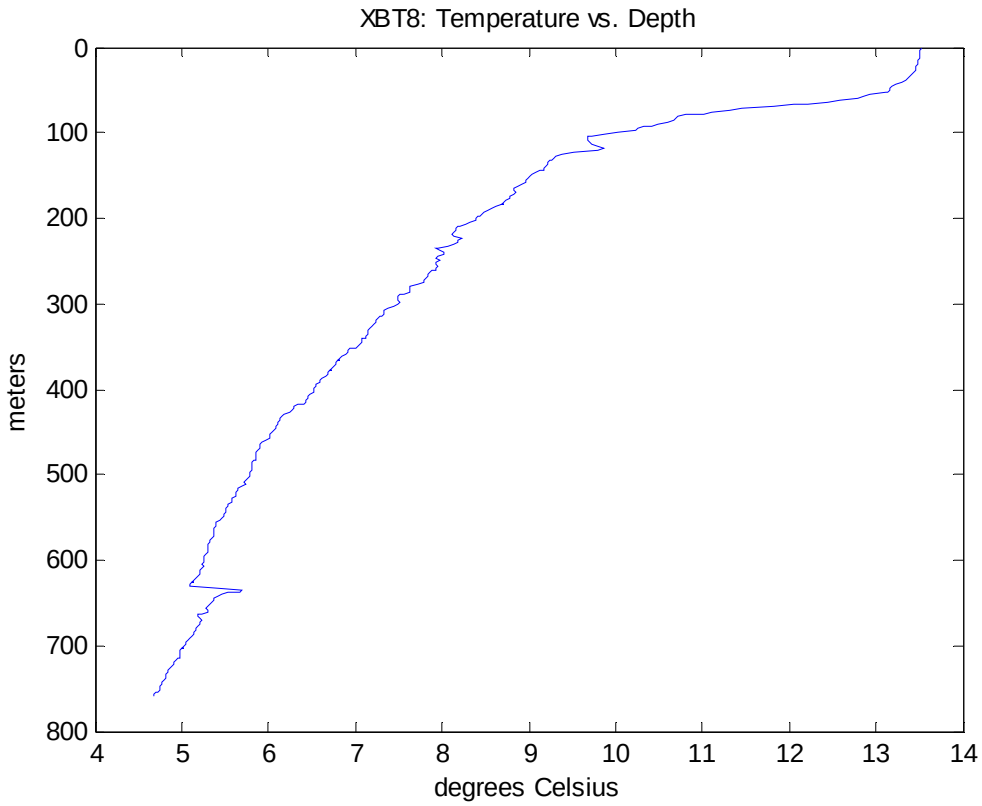
Appendix A: First table, position and date of CTD and XBT data used in this study. Second table, position of GDEM site used in this study, and the distance between that site and the XBT with the same number. CTD/XBT/GDEM numbers refer to the number in the cruise report; pair number refers to the pair numbering system used in this study for simplification and in the figures in further appendixes.

**APPENDIX B**
Locations where data was extracted



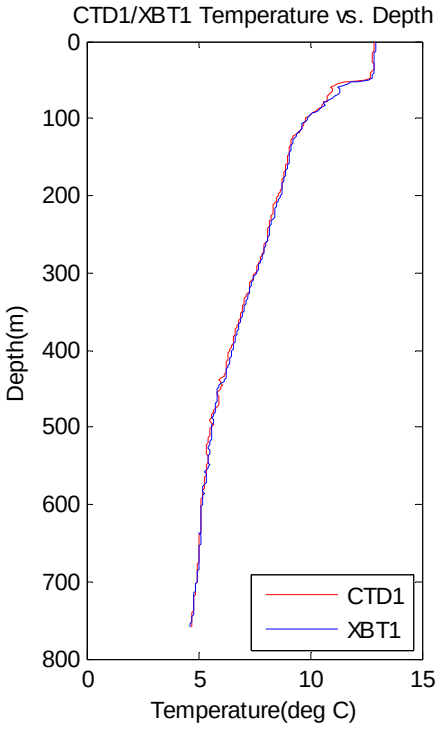
**APPENDIX C**

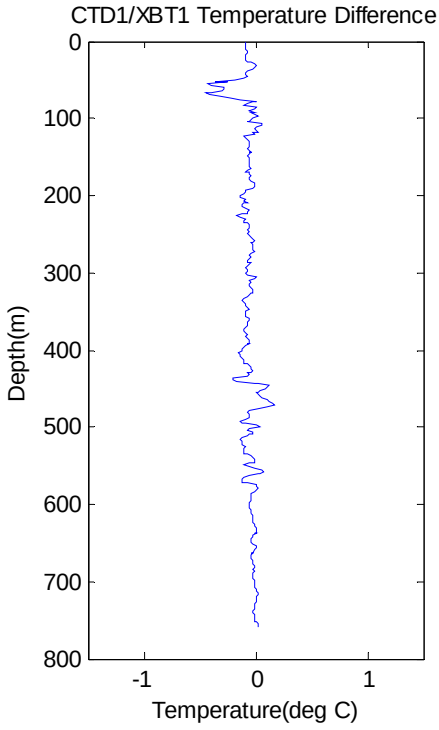
Bad Temperature Profile Plot

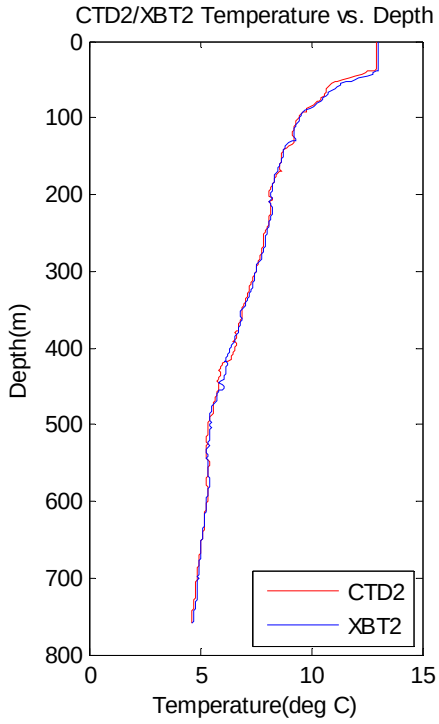


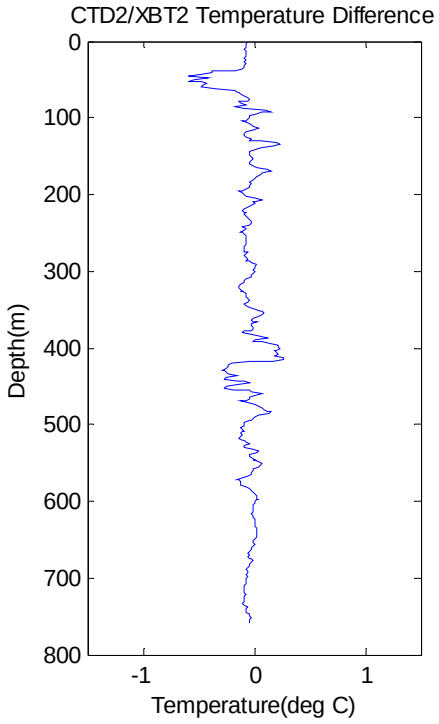
**APPENDIX D**

CTD and XBT Temperature Profiles and Difference Plots



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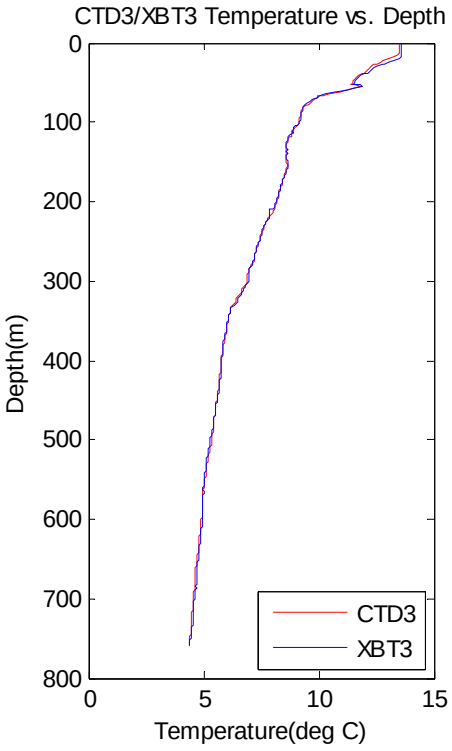


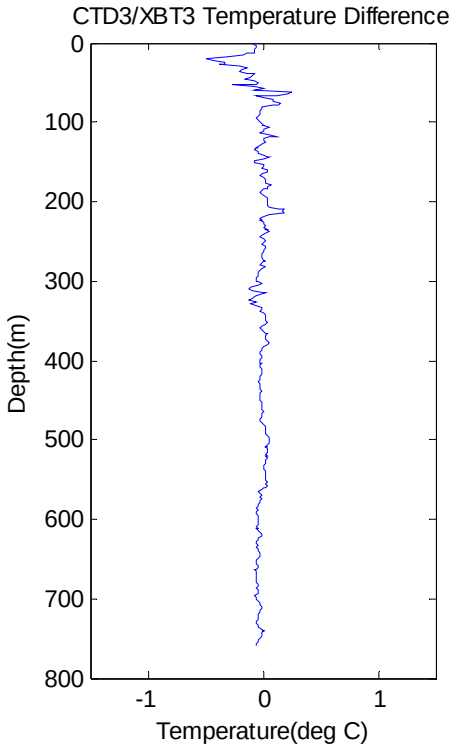


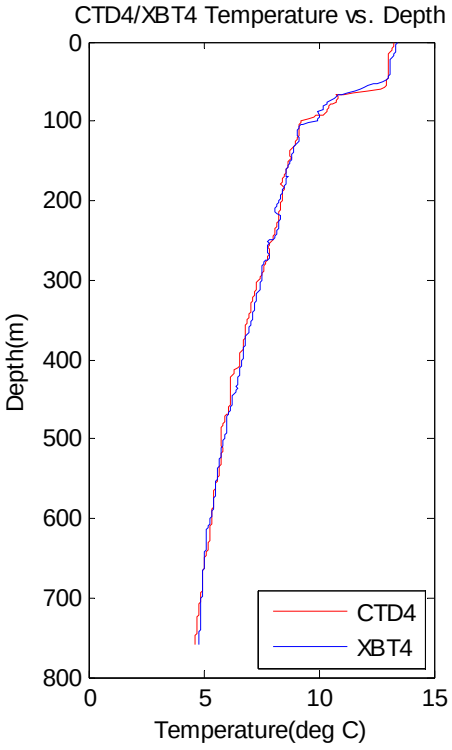


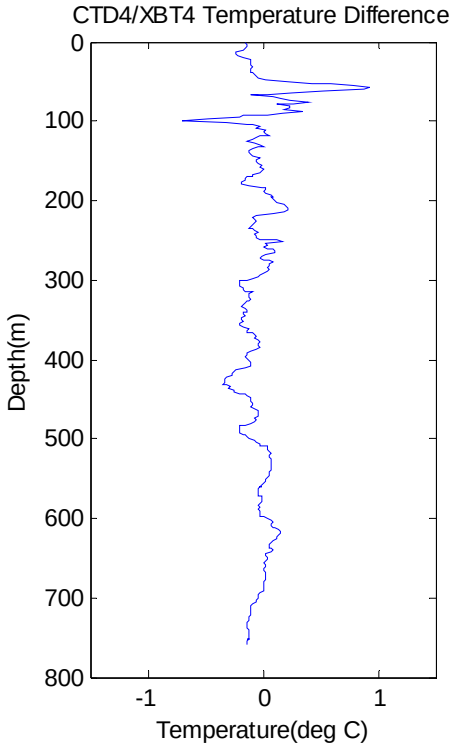

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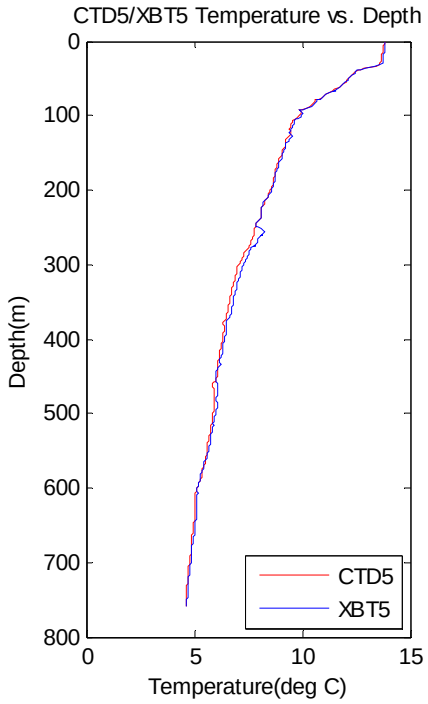
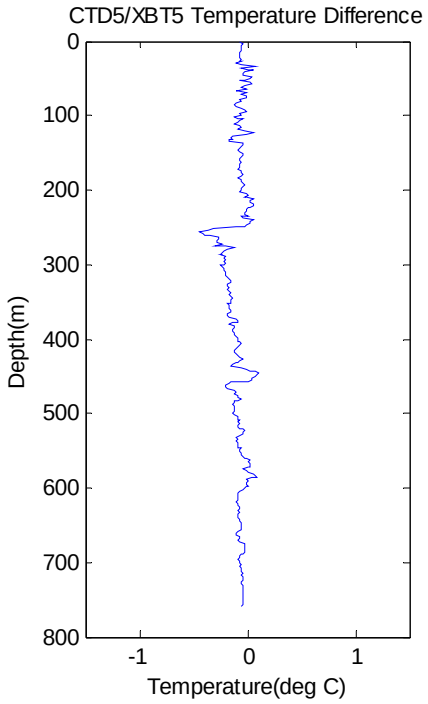
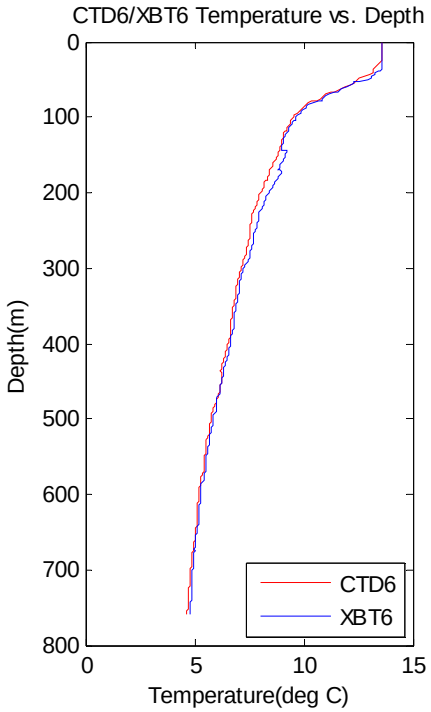
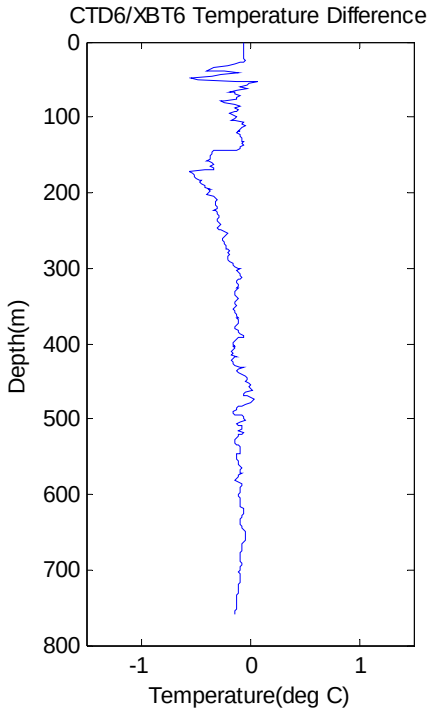


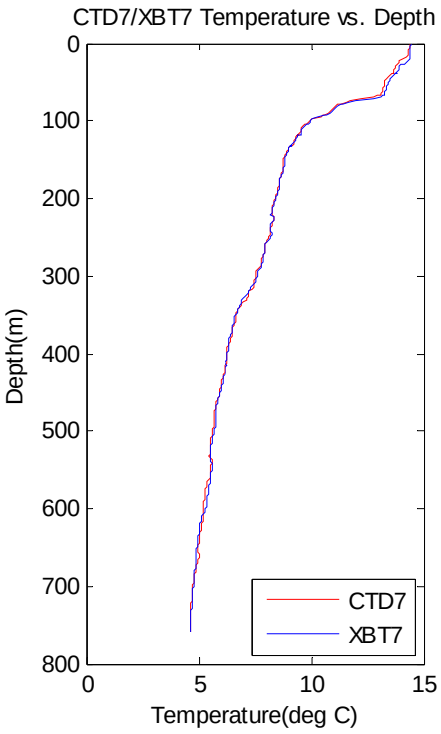



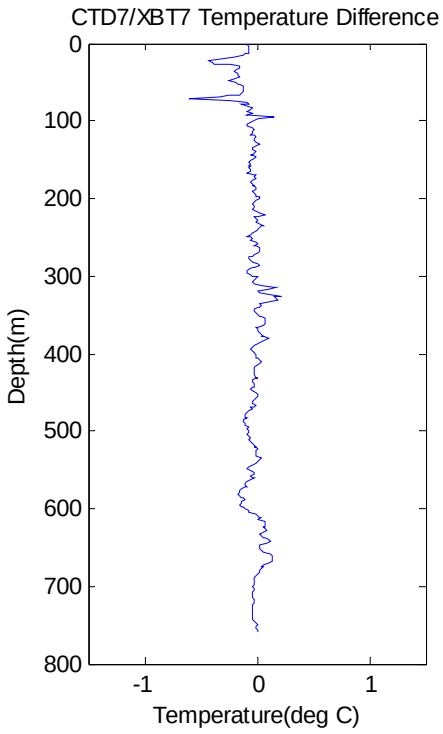



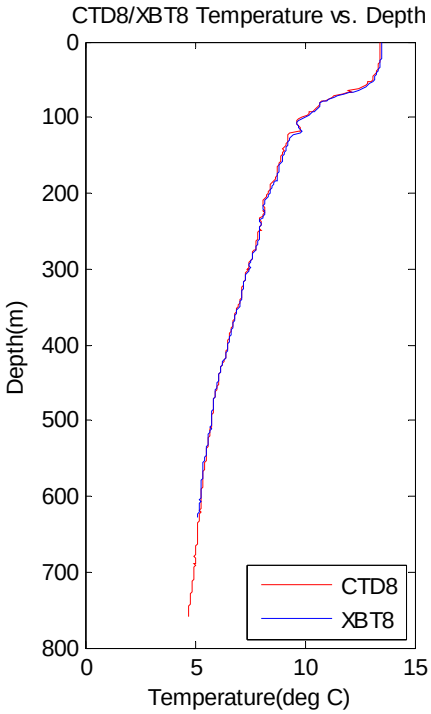



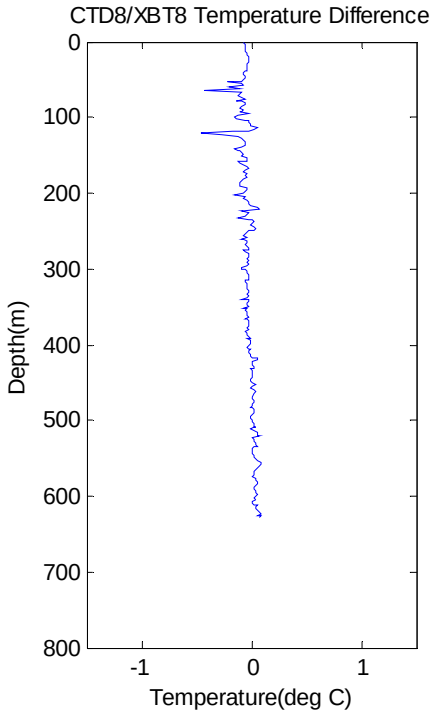
**APPENDIX D**

CTD and XBT Temperature Profiles and Difference Plots



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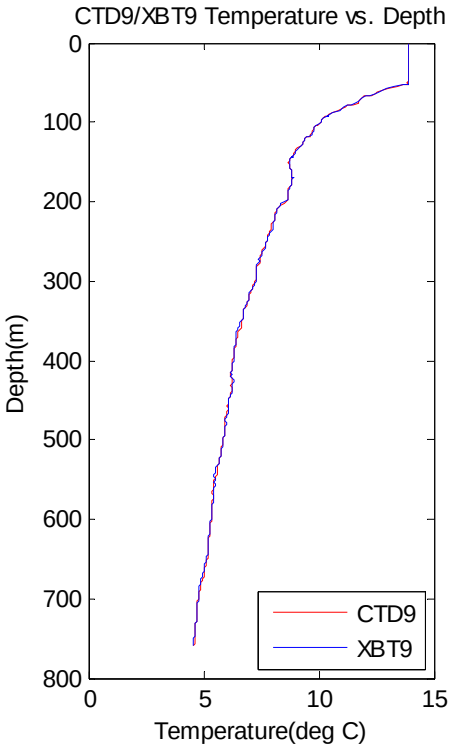


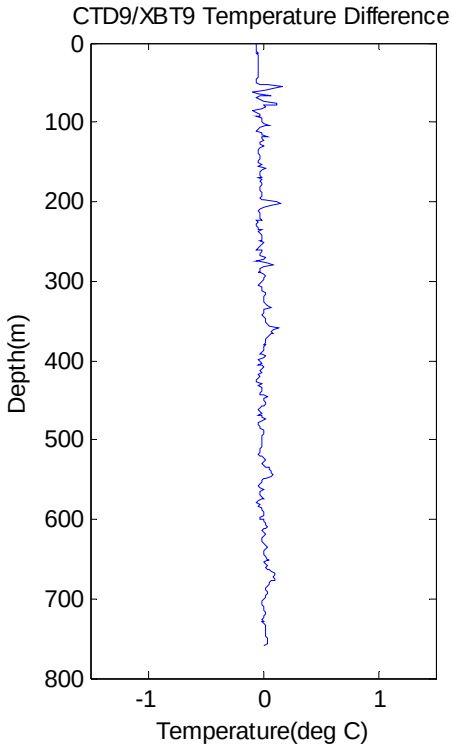


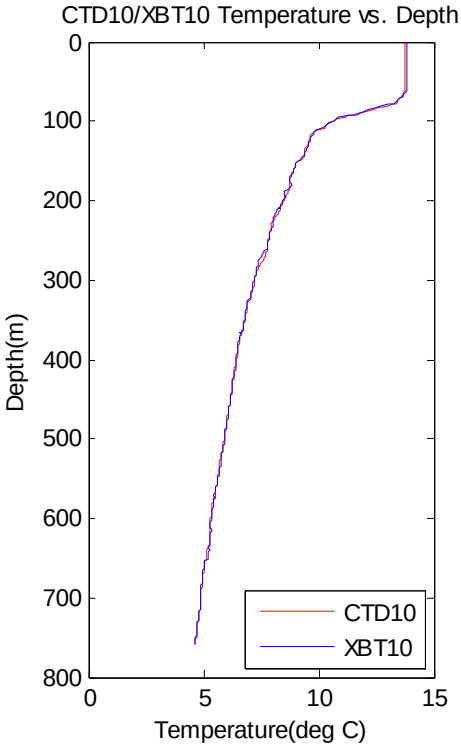


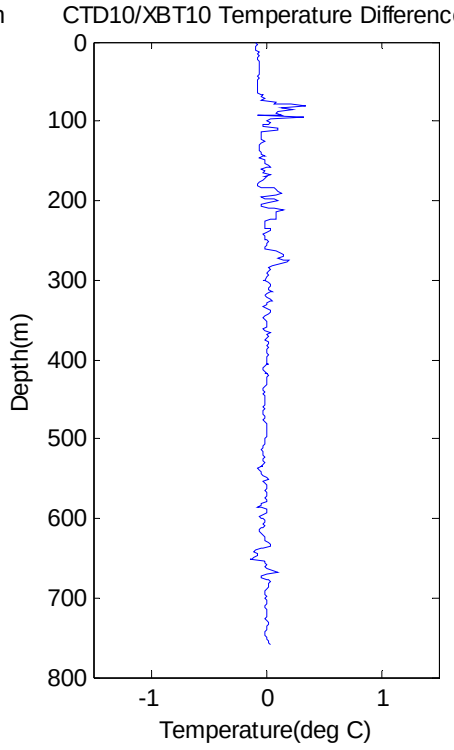

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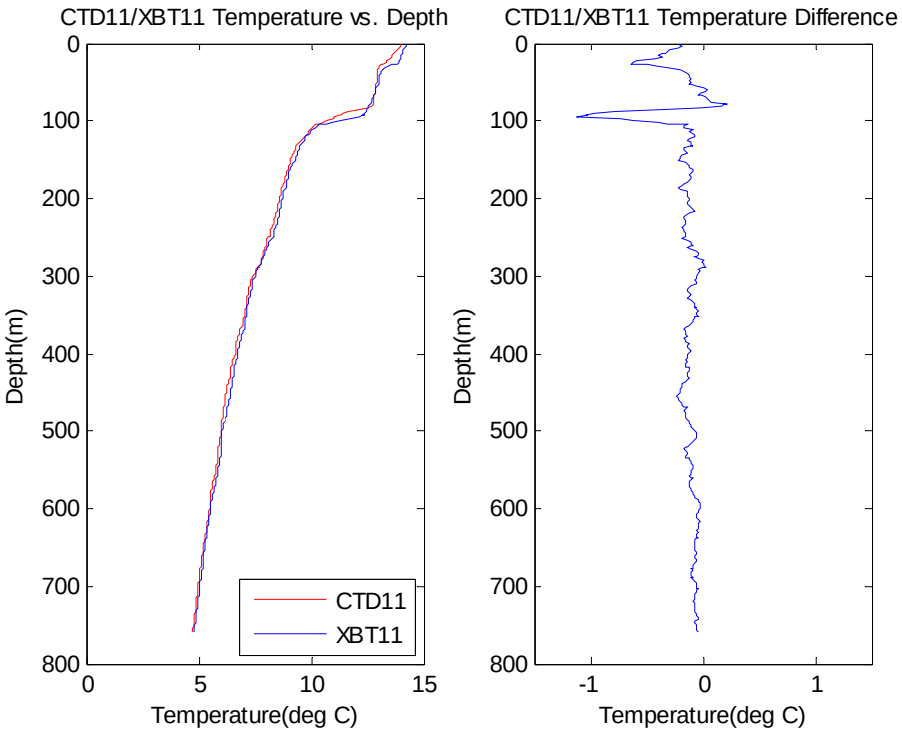
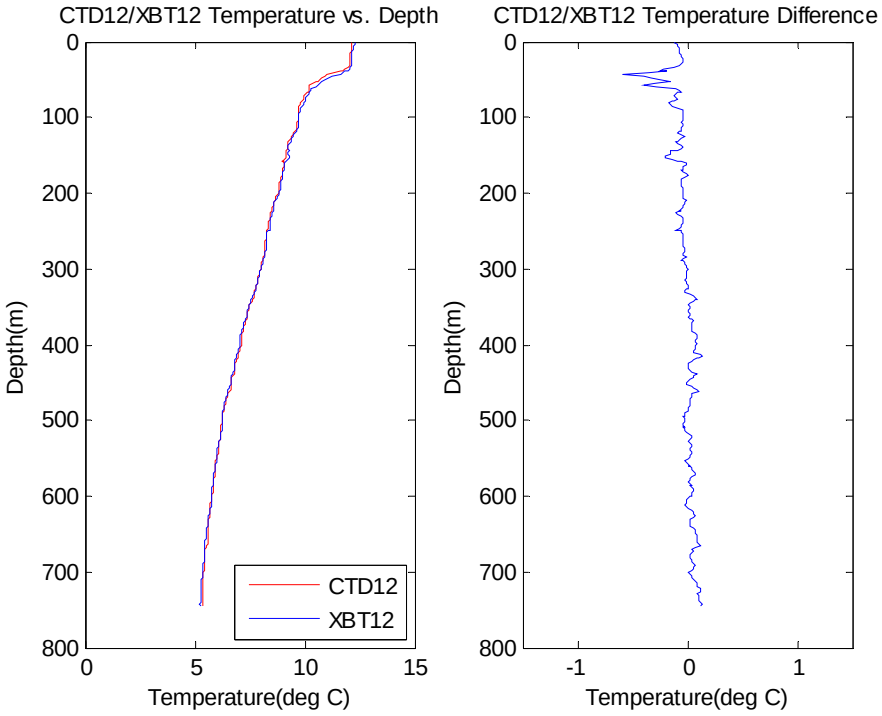
CTD and XBT Temperature Profiles and Difference Plots



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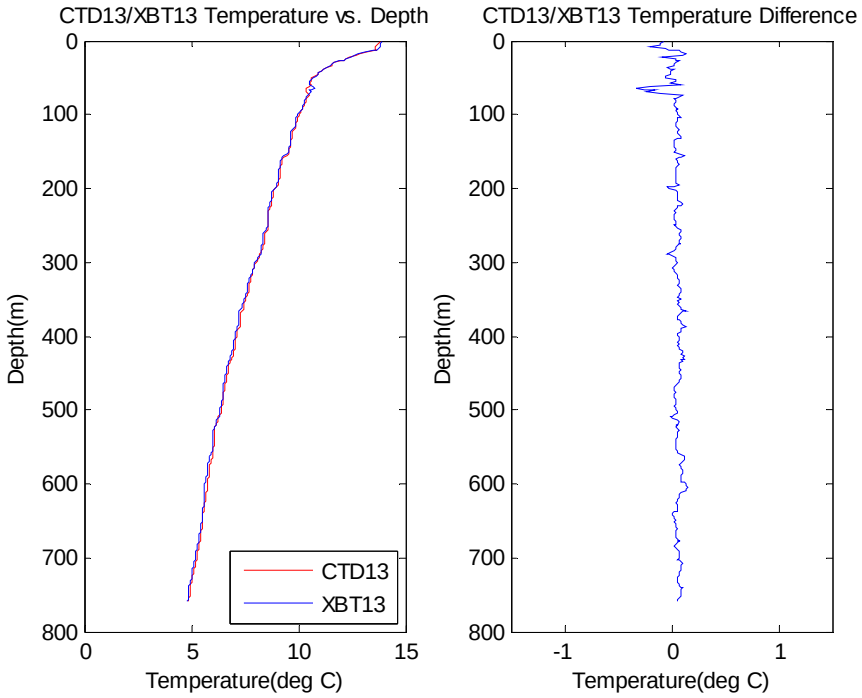
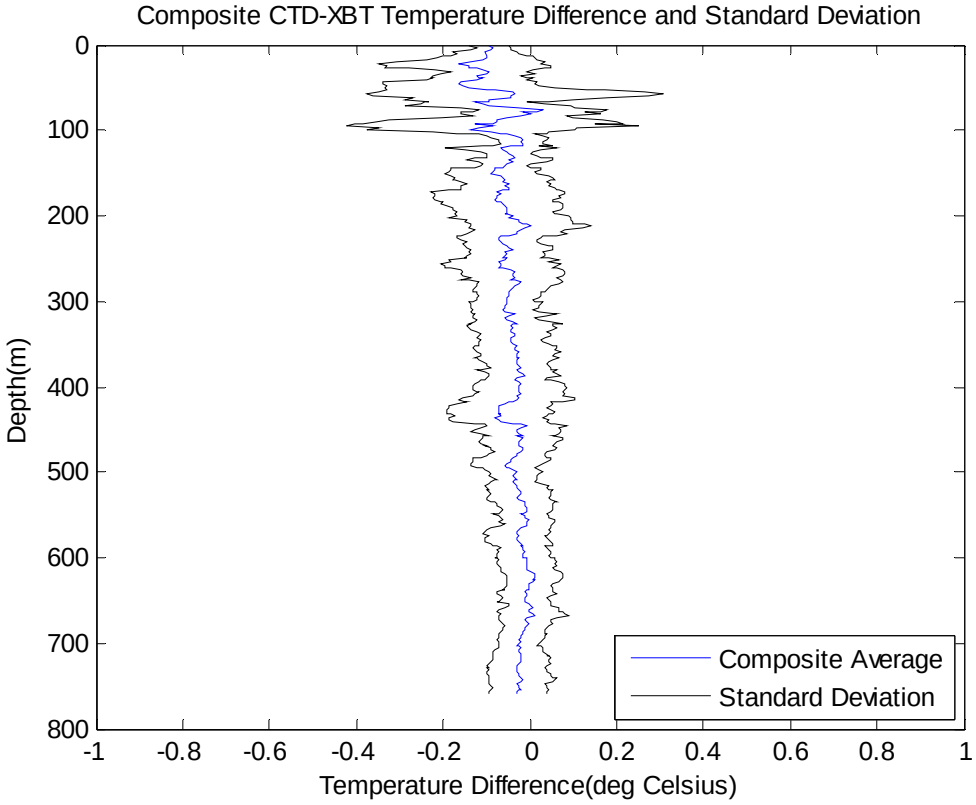
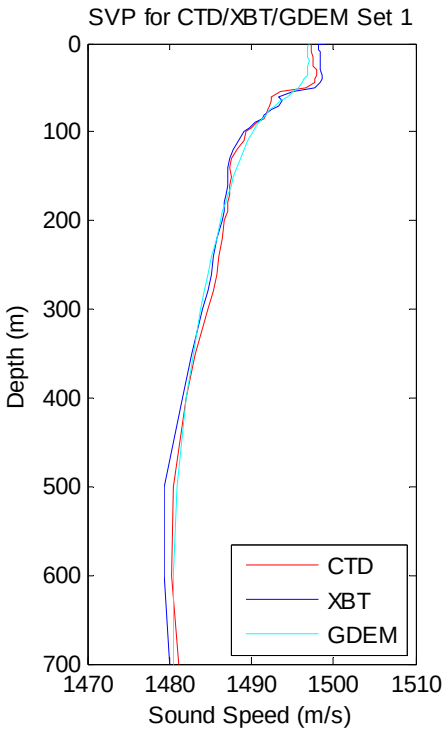
CTD and XBT Temperature Profiles and Difference Plots

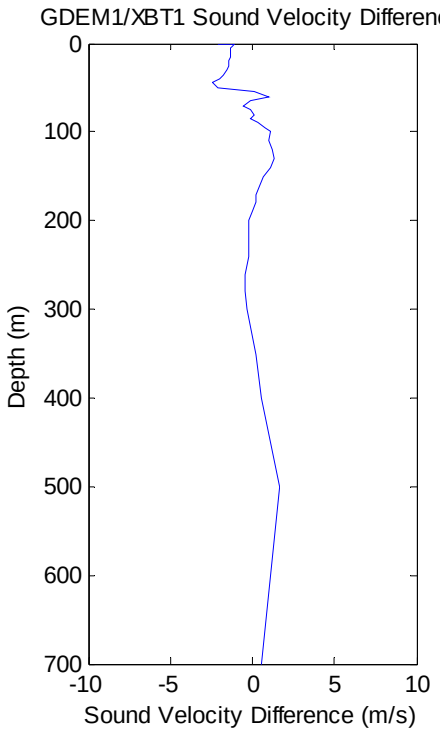


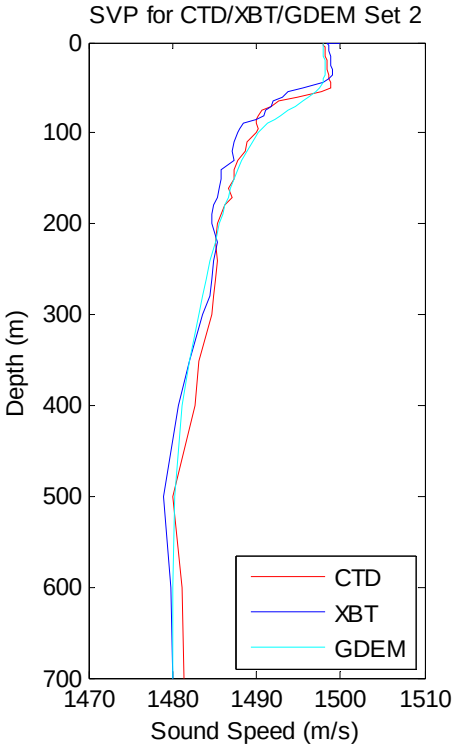



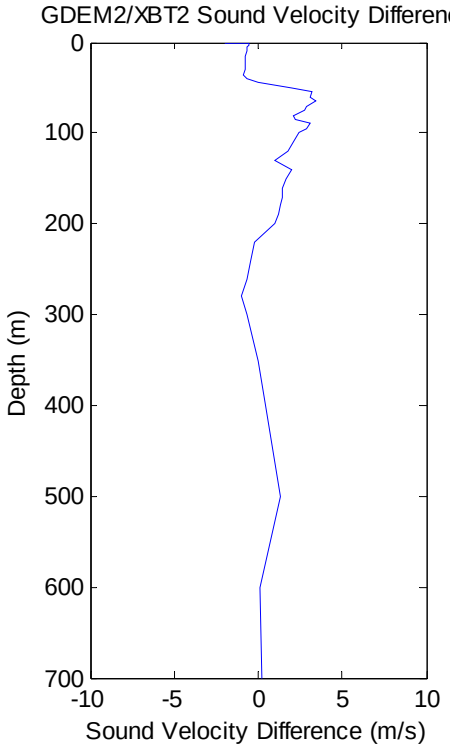
**APPENDIX E**

CTD and XBT Sound Velocity Profiles and Difference Plots



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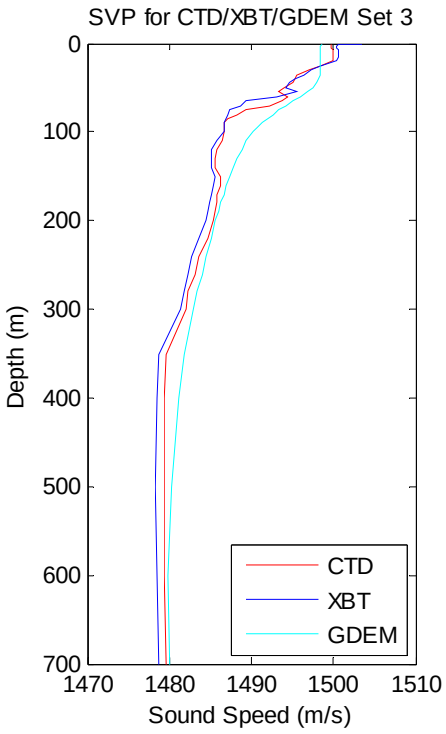
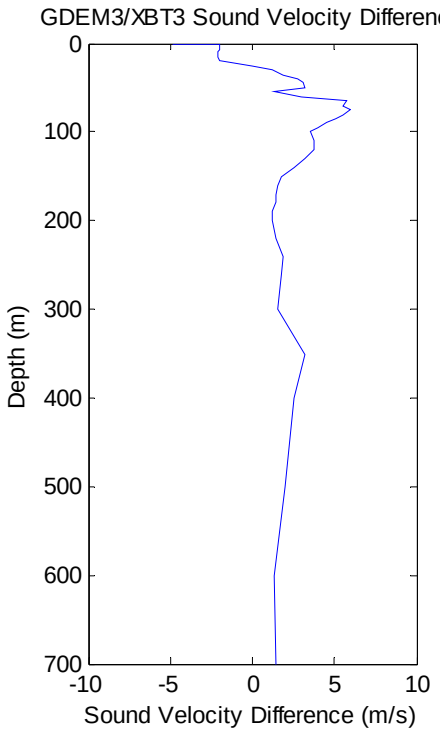
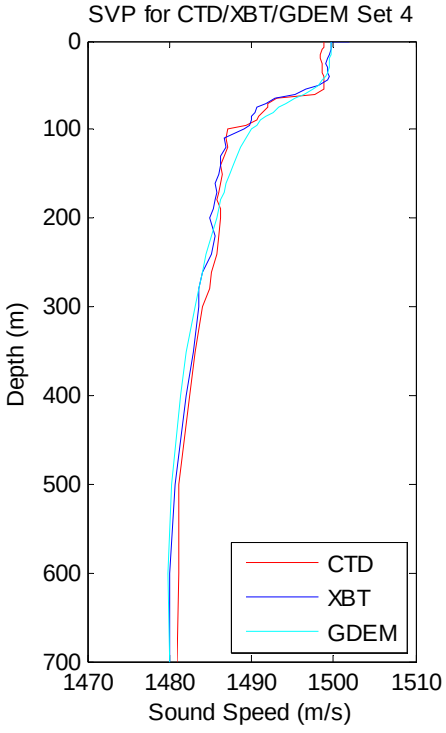
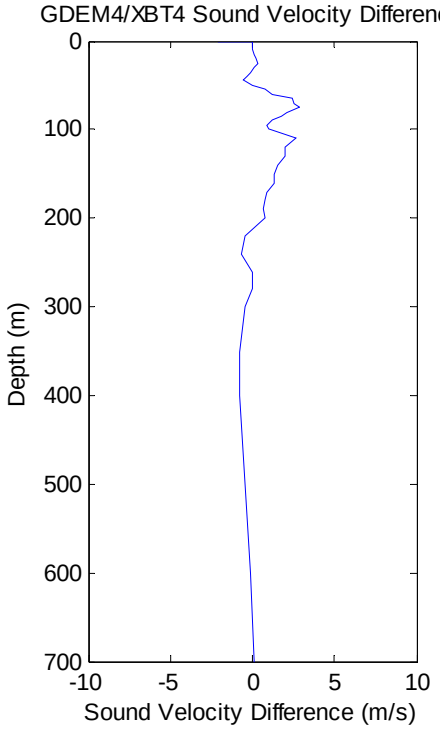
CTD and XBT Sound Velocity Profiles and Difference Plots



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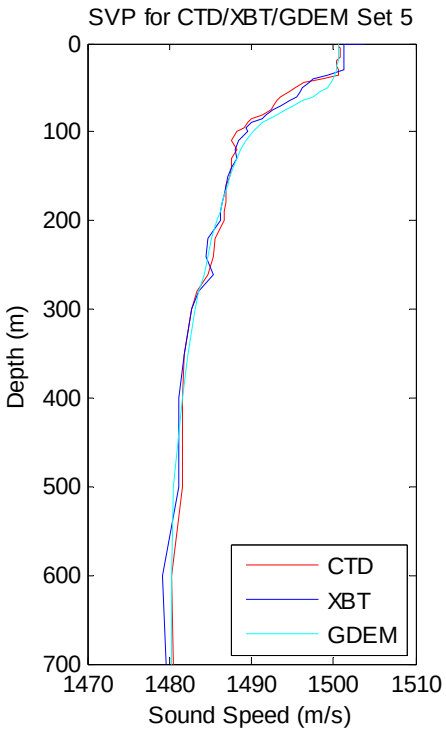
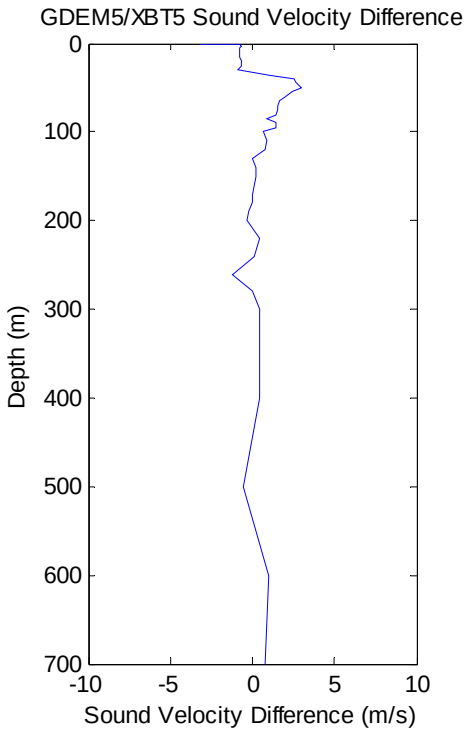
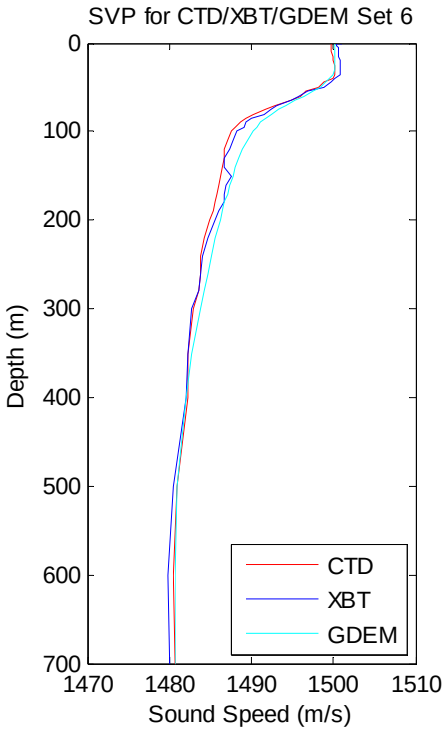
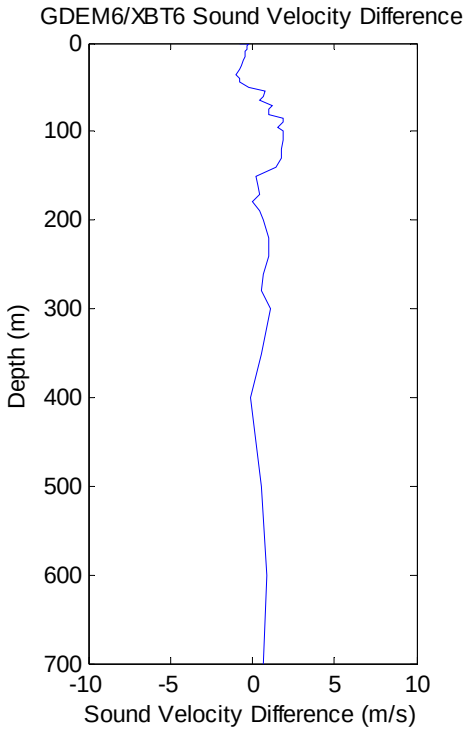
CTD and XBT Sound Velocity Profiles and Difference Plots



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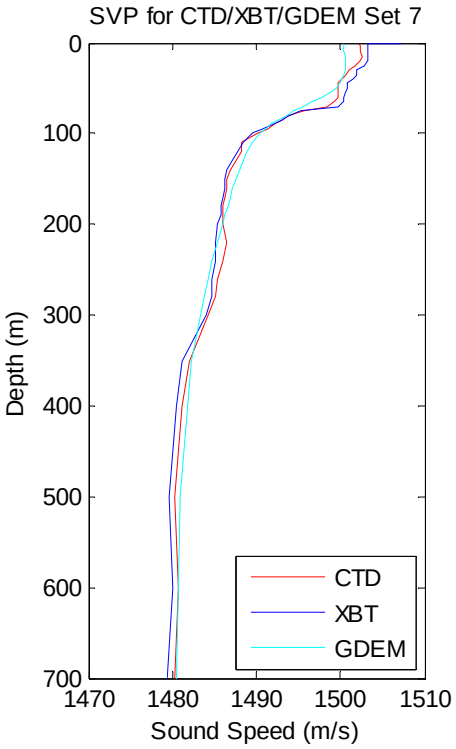
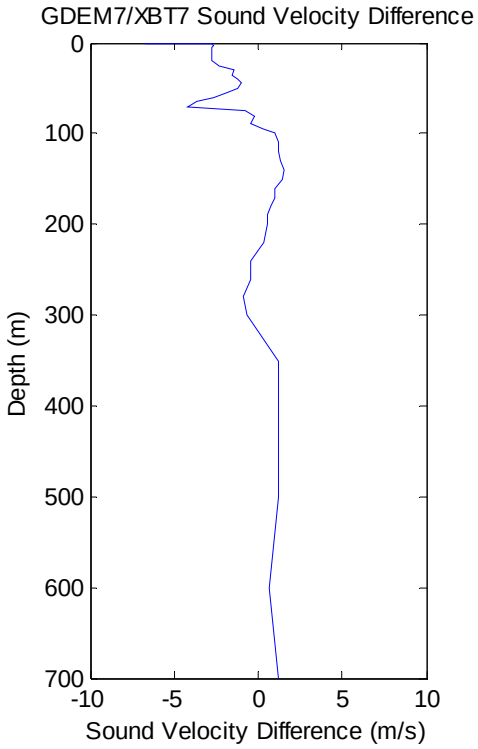
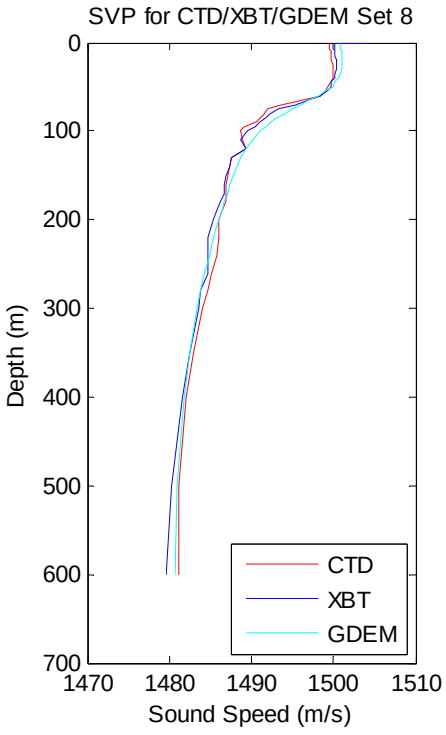
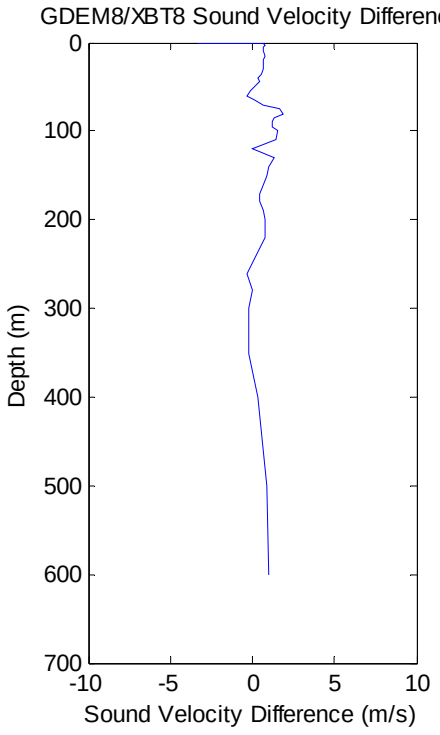
CTD and XBT Sound Velocity Profiles and Difference Plots



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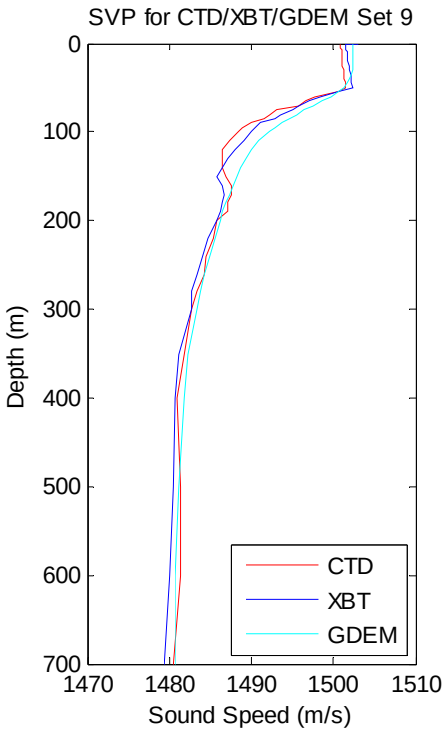
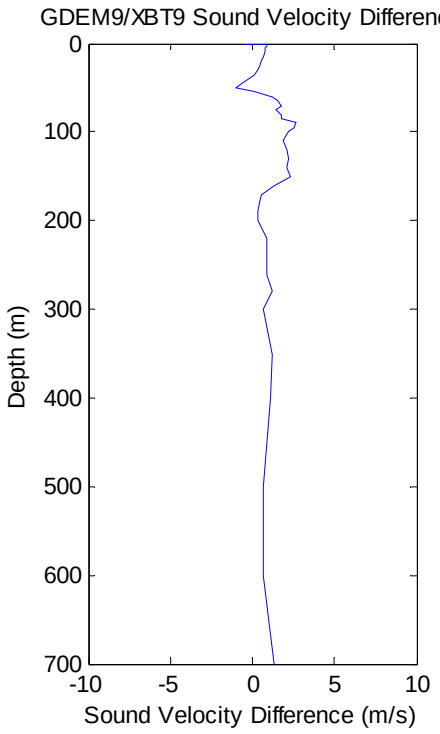
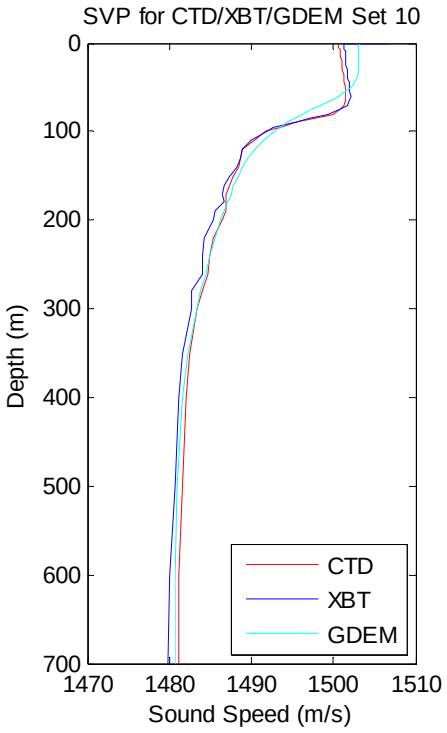
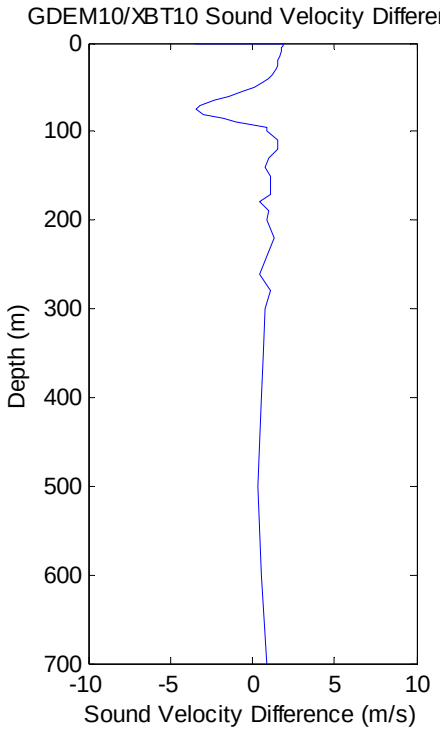
CTD and XBT Sound Velocity Profiles and Difference Plots



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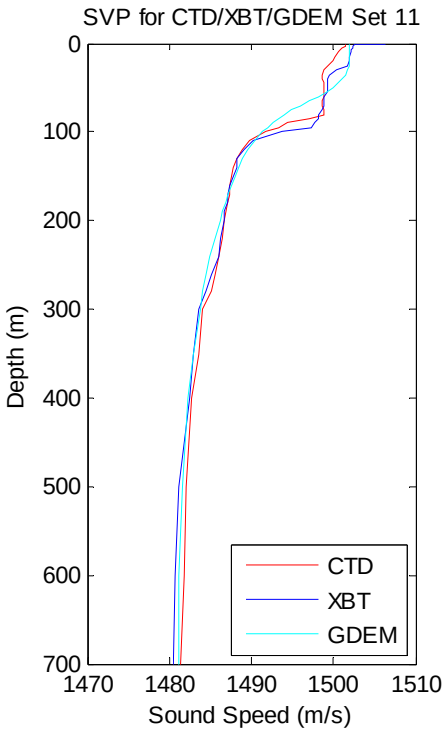
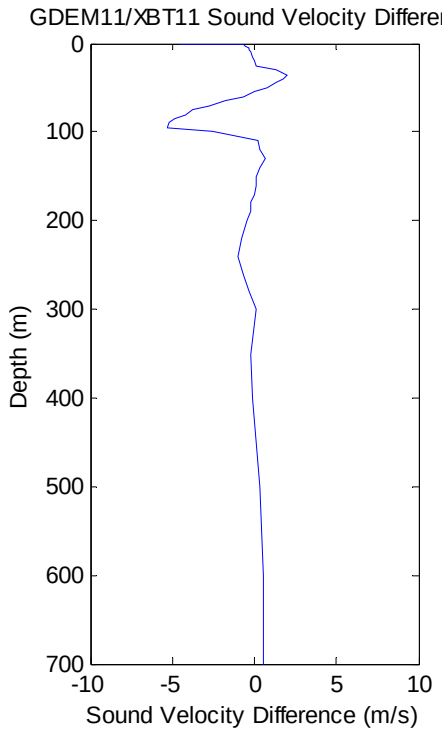
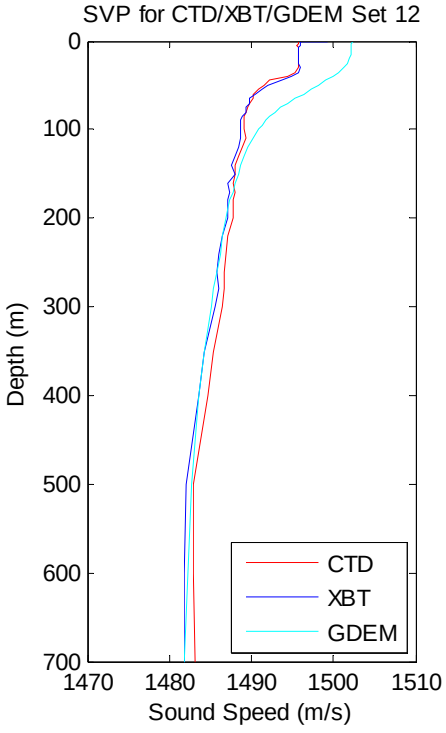
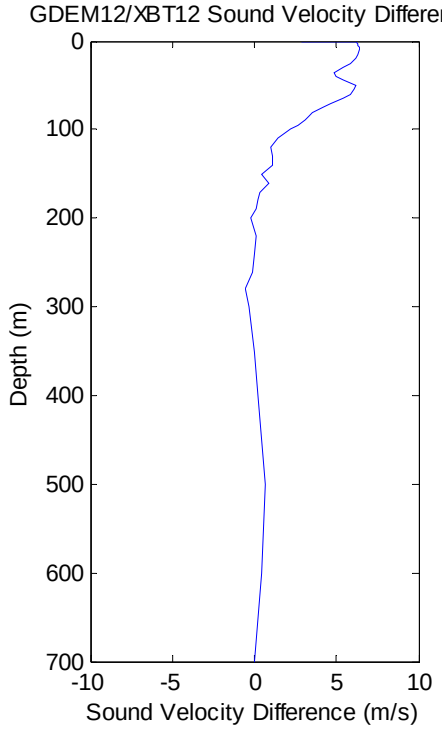
CTD and XBT Sound Velocity Profiles and Difference Plots



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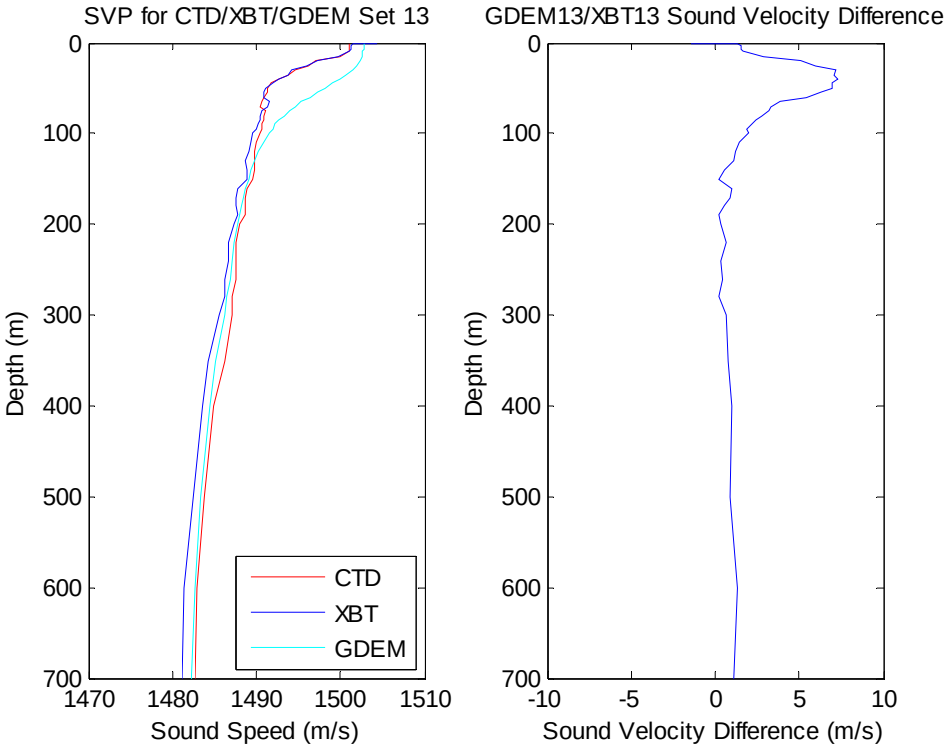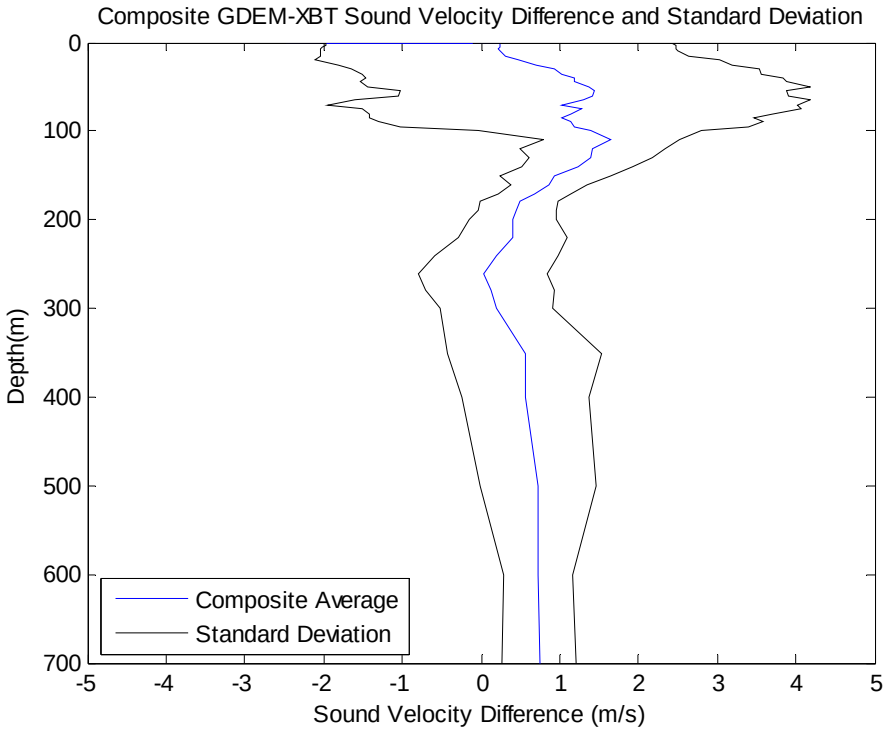
CTD and XBT Sound Velocity Profiles and Difference Plots